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Architecture Framework for Manufacturing System Design

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Abstract

An architecture framework which establishes a common practice for creating, analyzing and representing manufacturing systems during design and re-design processes is proposed. This paper includes a study of the main architecture frameworks and their use within a systematic design process for manufacturing systems. A class diagram is related to a physical architectural framework with manufacturing system components taxonomies that support it; it is applicable to manufacturing systems including RMS (Reconfigurable Manufacturing System).
As product development life cycle becomes shorter and shorter, a systematic, structured and effective approach is needed to design or reconfigure the manufacturing system as needed. The proposed framework is comprehensive and specifies the system representation from various levels and dimensions. This paper considers not only abstract and general representation, but also illustration examples to represent manufacturing systems designs.

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Keywords: Architecture Framework; Manufacturing Systems Design; Manufacturing Systems capability; Reconfigurable Manufacturing System

1. Introduction

The current high-changeable production context triggers changes in the manufacturing system design process. As a result, design solutions change at various levels and dimensions. Before dealing with changeability, the designer first needs a framework to understand and represent the manufacturing system capability at the different stages of process design. This paper aims to increase the knowledge regarding the relationship between system representation and system design process. Therefore the first section presents viewpoints from common architecture frameworks to represent a system and their applicability in a systematic design process. The second section presents a physical architecture framework with a class diagram supported by components taxonomies.

2. Manufacturing system design principles

A critical step in the system design process is to map physical solutions (resources, devices and arrangements) with their functional requirements. The representation of system capabilities supports the system design process. Before the systematic system design process, the viewpoints for system representation should be defined.

2.1. Viewpoints definition

Architecture frameworks that represent engineering systems may include different viewpoints. A survey of the viewpoints from the most popular architecture frameworks (Zachman [1], Sagace Matrix [2], DoDaf 1.5 [3], Cimosa [4], Aris [5], Pera [6], MDA [7], AFIS [8] and Pahl & Beitz [9]) has resulted to the following analysis/synthesis. The viewpoints are clustered in three dimensions:

- Static and dynamic dimension [8]
  - Structural viewpoint: it describes system entities, their arrangements and interactions. This `white box' or internal representation is useful for representing a holistic problem.

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- Behavioural viewpoint: it represents system behaviour through different scenarios (e.g. operating, maintenance, evolution). It will involve different state transitions on a time scale.
- Design domain dimension
  - Contextual viewpoint [1, 2, 3, 8]: it illustrates the finality of the system in its environment. It focuses on the interactions between the `black box' system and its context.
  - Functional or logical viewpoint [1, 2, 3, 4, 5, 7, 8]: it expresses what the system should do, without specifying how.
  - Physical viewpoint [2, 3, 7, 8]: it is how the system realizes the required functions at the physical level; "how" the system should do it and "with what". System components and their arrangements are specified. Different granularity levels for the physical representation may follow a common up-down design process [1, 4, 5, 6, 9]: generic level (e.g. a conceptual decision, choice of technology), embodiment level (physical organization that might be for objects such as data, people, resources etc.) and detail level (parameterization within the defined components).
- Abstract levels dimension [4, 5, 7]
  - Independent model: it represents an abstract class of systems; a system platform that may later support system instantiations for specific functionalities.
  - Specific model: it responds to a specific context, task or functionality. It is derived from an independent model, thus taking advantage of reusing the model already in place. According to different strategies and system contexts, segmenting abstract levels is more or less relevant. As far as Reconfigurable Manufacturing Systems are concerned, the required changeability should lead to an in-depth study of this model paradigm.

2.2. Manufacturing system design process

This section presents a general guideline encompassing the sub-activities for manufacturing system design, which is illustrated in Fig. 1. It is inspired from areas of research such as engineering systems design [8], process planning for different granularity levels [10], resources selection and the allocation of system capabilities [11].

2.2.1. Inputs for manufacturing system design process and collaboration with process planning

The inputs of the manufacturing system design problem are a production context defined by: a product family, volumes, variants with degrees of variability and a pre-process plan describing product features, sequences and precedence constraints.

In fact, the main supporting decision in the system design process is the process planning which links product features and their realization process by the manufacturing system. Concurrently, the optimal selections of production methods, resources and arrangements support the process planning activity. For this reason, the presented design process collaborates with different levels of process planning [10]. It performs different outputs: generic process plan decides on the classes of the processes, according to product features and precedence constraints it associates required and available capability profiles [11]; macro process plan identifies an optimal process sequence from process and product precedence constraints [12]; detailed process plan is concerned with the allocation of process to specific resources, devices, fixtures or tools; and micro process plan specifies optimal operating conditions and machines instructions.

2.3. Decomposing the problem into functional requirements and components

The requirements analysis (A1 in Fig. 1) is the first activity that analyzes the system context (i.e. *contextual viewpoint* within *structural and behavioural viewpoints*) and derives the main functional requirements (e.g. multi-domain process plan for a product family). The decomposition of the functional problem into sub-problems (A2 in Fig. 1) entails logical components. It follows the *structural and behavioural functional viewpoints* of the system. The last level of this functional decomposition should allow the system capabilities to be potentially matched to system component solutions [8]. This activity (A4 in Fig. 1) that links *functional domain* to *physical domain* is enabled by the representation of the desired or existing physical solutions. Coupling matrix (e.g. DSM) or methods for mapping (e.g. Axiomatic Design) are other support tools.

Let us point out that there is no bijection between the functional and the physical domains. The decomposition process is iterative between these domains through different levels of physical description. For instance, a handling function would require a physical handling system where sub-functions may require buffers, grippers, a robot and other devices.

2.3.1. Architecture design

Once the main functional modules forming the structure of the system have been selected, the functional architecture is then designed as an arrangement of these modules (A3 in Fig. 1). Although some manufacturing system design methods stop at components selection (e.g. resource family, devices, tools), this holistic perspective guarantees the coherence of the design at the system level. The expected and derived requirements from the *behavioural viewpoints* (e.g. sequence or scheduling constraints) lead to the functional architecture design. The interfaces of the functional components may also be considered as functional components that will later affect the physical solutions. After the functional architecture, comes the physical architecture (A5 in Fig. 1). Once again, the mapping from *functional domain* to *physical domain* is enabled by taxonomies of system arrangements (e.g. layout taxonomy). Since the system is made of different kinds of components which belong to different manufacturing areas (cells, transport systems, devices, workstations etc.), delivering an optimized solution is the objective of this rational design process.

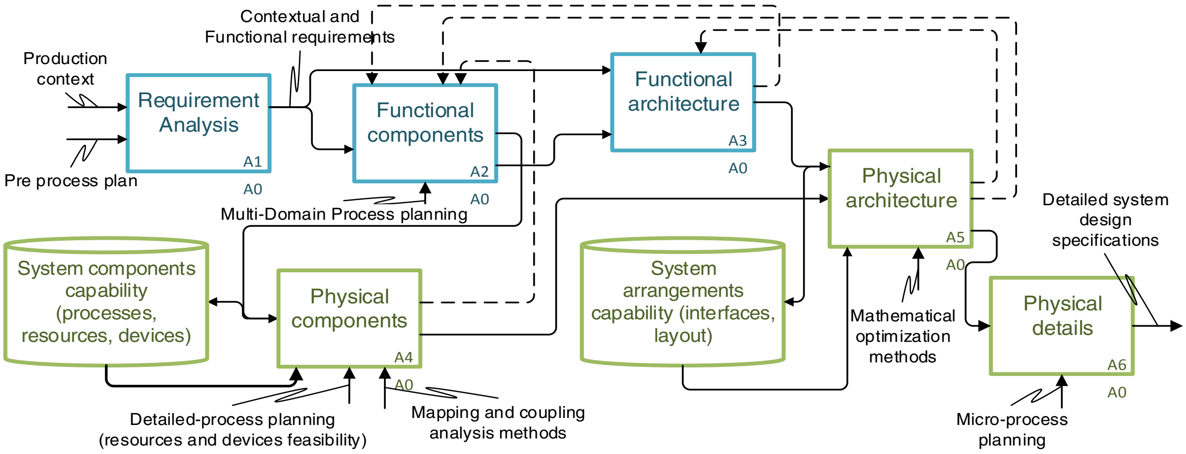

Fig. 1. IDEF0 – Manufacturing system design process with supporting system capabilities taxonomies

If some areas are decoupling in terms of design solutions, sub-problems may be segmented in order to use mathematical optimization methods collaborating with the global architecture design (e.g. detailed-process planning for a type of machine, facility layout, operations assignments, line balancing, pallet configurations, configuration setup synthesis of RMT (Reconfigurable Machine Tool), capacity scalability planning, material transport system selection, facility layout decision or reconfiguration of the control system).

2.3.2. Detailed decision or parameterization

Physical decisions are first made at *generic and embodiment levels* [9]. The last design activity (A6 in Fig. 1) is the *physical details* at the machine level (instructions, codes, parameters). Collaborations with micro and detailed process planning for each resource will give information about feasibility and costs. To do that, E. Jarvenpaa [13] suggests a holonic reasoning where each holon represents machine parameters and negotiates with each other on the best resource selection.

2.3.3. Test and integration

From the final system design specifications, the verification of system requirements, the validation of initial requirements and the qualification in an operational environment are applied to system modules, components and finally to the whole system.

3. Manufacturing system architecture framework

The main purpose for representing the system's capability is to support frequent system design decisions. As it was previously stated, the capability of the system to deal with new production contexts (e.g. new product family, new volumes, new process planning or new technology) is related to the knowledge and understanding of the existing or the desired system possibilities. Therefore, the representation of manufacturing system components - in functional and physical domains- is a key-enabler for design and re-use in a changeable context. This dual representation supports the critical activity of physical decisions in the rational design process. It also supports the process for describing the system's capabilities, that is to say referencing the functionalities of an existing physical system. The following taxonomy is an ontology to describe a manufacturing system in terms of functional and physical solutions. According to the previously proposed architecture framework (section 2.1), this section will only focus on a physical viewpoint to represent the manufacturing system at generic and embodiment levels. Depending on the application field, different kinds of objects and interfaces may be focused on in the physical domain (e.g. in an informational system, objects are data and procedures; in a mechanical system, objects are material features; in a business system, objects are financial, departments and human resources).

3.1. Structural hierarchy of a manufacturing system

Manufacturing systems are made of different kinds of physical objects, either informational or material, thus at different hierarchical levels and for different oriented functionalities. System components may be static objects or flow objects (energy, tools, waste material, raw material, parts, sub-products and data).

We differentiate between three hierarchical levels in the physical manufacturing system according to Scholz-Reiter [14]. Fig. 2 is an illustration of the following description.

- At the system level (i.e. shop-floor), a manufacturing or assembly system is defined in the physical domain as a set of workstations or cells interlinked with storage and transportation systems. Together they manufacture a work-piece or a sub-product family. The whole product is manufactured at the upper level [15].
- At the sub-system level, a cell or a workstation is made of an arrangement of resources (e.g. human resources, facilities, robots, transfer systems, machine and different devices) in order to support a set of different processes or operations. However, depending on the complexity of the sub-system, a production unit, a storage system or a transportation system may be made of one or more resources. For instance, a single piece of equipment would be a CNC machine; an AGV or a conveyor belt for a transportation system; a simple sorter

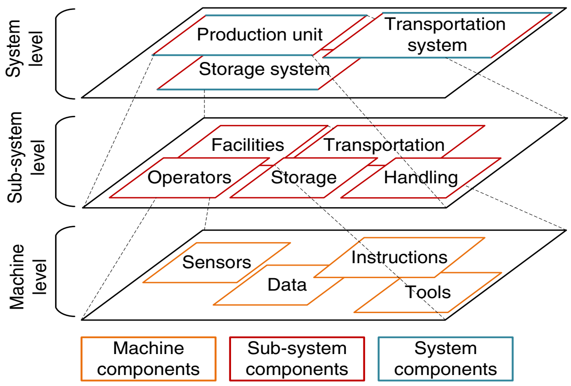

Fig. 2. Physical hierarchical levels illustration

buffer as a storage system. In these examples, system components are merged with components within the sub-system. Also a single resource or a workstation would only manufacture a sub-product element or feature [15]. Otherwise, a cell would support manufacturing several features as a feature family, often grouped within one unit according to their similarities in the technology process.

- Then at the machine level, the selection of components, devices, tools, grippers, data, programs and their arrangements will be done according to the operating task required by the equipment.

As a result, through these different levels a structural representation of the manufacturing systems components at system and sub-system levels is developed in the following paragraph. This representation is illustrated by the class diagram in Fig. 3 using the modeling tool UML (Unified Modeling Language) which includes aggregation relationships. Components of the system and sub-system classes are attributes and the functionalities are methods.

The class diagram represents the possibilities to design or represent an existing system according to the three levels defined above. It also includes particular cases. Firstly, the system and sub-system levels may be merged; it means that the system is quite simple when sub-system components are directly machine components (e.g. tools, grippers, sensors). For instance, a manufacturing system made of different CNC machines has two levels: the system level (CNC machines inter-connected by a conveyor) and the machine level (tools, spindles, grippers and data). A second particular case would be the co-existence of two layers within the subsystem level: a production unit would have an internal transportation system or a buffer system to ensure the continuous supply of parts; which may include other handling devices (e.g. robots).

3.2. Functional and physical manufacturing system components class diagram

Functionalities (i.e. methods) and attributes of the class diagram in Fig. 3 are explained in detail. For the attributes presented with an asterisk in Fig.3 there are several physical solutions available. A review of the different taxonomies that are needed to support these physical attributes is presented in Table 1.

System - shop floor level

We differentiate *technological class* for the methods of the system (i.e. transforming parts with manufacturing or assembly process) from *logistical class* (i.e. storing and conveying parts, materials or tools at the system level). The informational operations that control and supervise the system are encompassed in the *informational class*. This segmentation is justified by the later allocation of physical units that fulfill these different process functionalities (i.e. production unit, storage system, manufacturing transport, control system and production system control).

Three kinds of attributes are considered: system flow objects (*flow objects class*), system components (*component class*) and arrangement of components (*arrangement class*}, from which the layout (*layout class)* -representing physical arrangement of facilities- inherits.

At the system level, *flow objects* may be *raw part, sub-products, energy, waste material* and *control data*.

The system components are the *production system control* (e.g. MOMS: Manufacturing Operations Management Systems), *production units* (e.g. cells or workstations), *storage system* (e.g. warehouse) and *transportation systems* between these units. *Waste material managing system*, *data network transportation* (e.g. LAN network) and *energy transportation system* are also components of the system.

Finally, the system is characterized by the physical arrangement of units (i.e. layout) within the *system type* and the logical arrangement representing the informational system (*system control*).

Sub-system level: production unit class

The standard VDI 2860 details the general functions of an assembly station: handling (feeding materials or tools in order to dispose and make them in a ready position), joining, checking (testing quality, inspection), adjusting (refining tools, parts supplies, products) and special operations (e.g. identification, labeling or any necessary post-process operation). From the standard VDI 2860, we derive these general functions of an assembly station to methods of any production unit, manufacturing or assembly (i.e. *Handling, Processing, Checking, Adjusting, Special operation, Control and Monitoring* methods). A *processing method* which is generic to any technology process is added. These functionalities may either be from the *technological class* (e.g. processing) or the *logistical class* (e.g. handling). *Handling* is decomposed into sub-functions in VDI 2860: buffering, moving, changing quantity, fixing, checking. It could be a start for defining methods in a *handling system class*. As a result, instances from the *transportation system* and *storage system* may also be included in the production unit. The attributes of a production unit are inherited from the *flow objects class* (i.e. flow objects going through the production unit) and the *component class*. It includes *process control system* (industrial control system as SCADA or smaller as PLCs), *handling system* for a micro-logistical task, *identification facility*, *periphery facility* according to the special operations needed (e.g. doors for safety reasons, identification equipment etc.) and *inspection facility* that checks quality requirements on parts or products. The *process* *enabler class* component is the *production facility*. Then, the arrangement of all the derived physical components is represented within the *layout class* according to the production unit type.

Sub-system level: storage system class

The basic purpose of a storage place is to keep stocks and provisions of work-pieces, sub-products, raw parts, load carriers or tools. The usual steps of a storage process are: receiving storage units, identification and quality verification of units, determining location, dispatching units in a store place, holding units in a store place, removing units and controlling operations system. We differentiate *storage objects* (raw parts, tools, load carrier or sub products) from other components [16] such as: *storeplaces*, *storage devices* that fulfill the work function by storing and retrieving units, *load handling devices* or *internal transport system*. Other attributes are the *storage process control system*, the *identification facility* which identifies the storage objects and the *periphery facility* for other purposes. The *layout class* is once again used to represent the arrangement of the previously listed physical objects.

Sub-system level: transportation system class

A transportation system is related to a technology used to move objects from one location to another (e.g. between production or storage units). The main *logistical class* function of a transportation system is *transporting*; it may include an *identifying* functionality to control transported objects and a *control and monitoring* functionality through the control system. The components of a transportation system are: the *transportation devices* which directly result from the chosen technology, the *transported objects* which may be sub-products, raw-parts, tools or load carriers, the *identification facilities*, the *picking stations*, the *delivering stations* and a *process control system*. The *transportation system type* defines the transportation network.

Conclusion

The architecture framework increases the relations between the system representation and a rational and systematic design process; it constitutes a great support to represent the system at different levels through different domains all along the process. Thus, a class diagram representing manufacturing systems across different physical and functional perspectives and an in-depth physical taxonomy have been presented. It is a preliminary step in order to deal with complexity brought by changeable and reconfigurable manufacturing systems. Future work will include specific reconfigurability and changeability enablers to the design process framework.

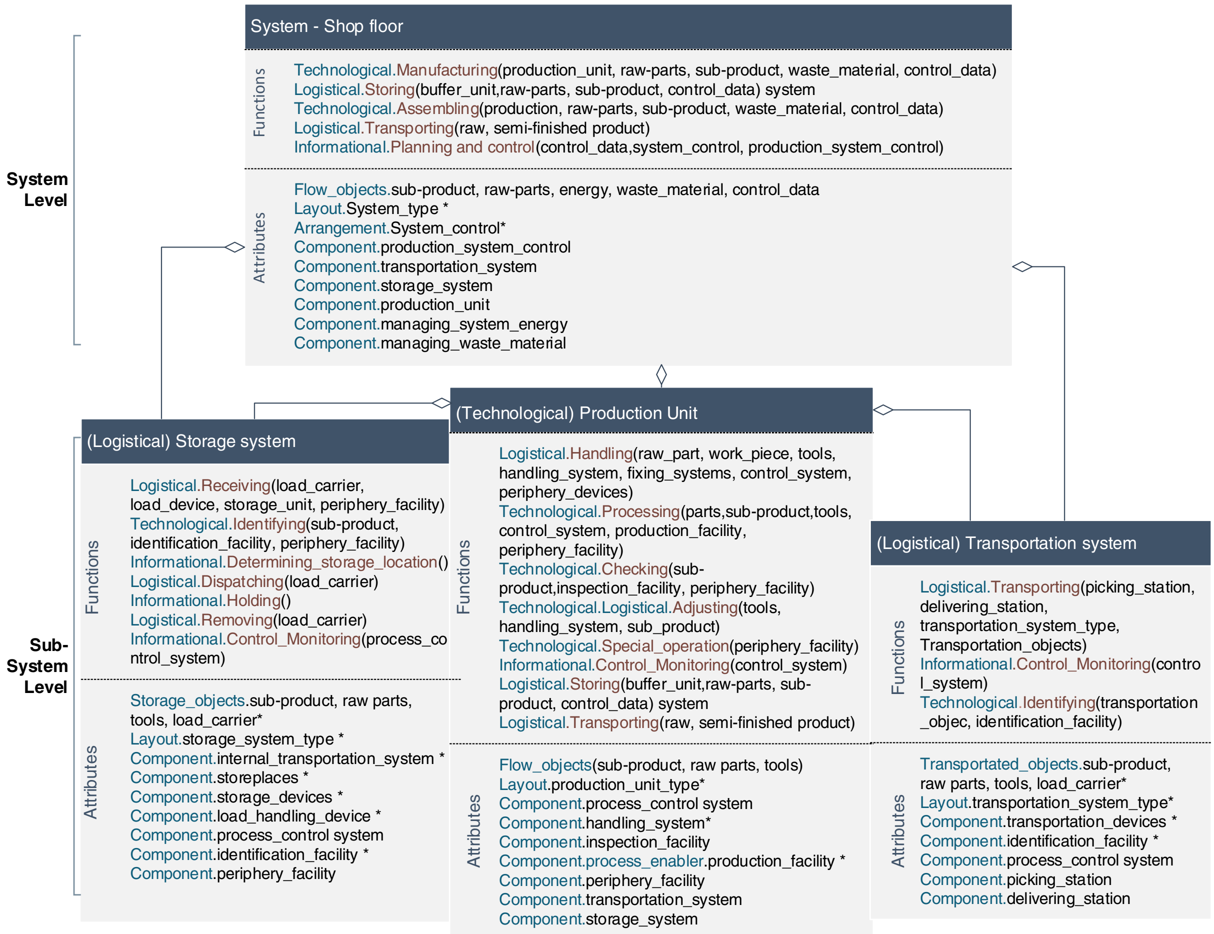

Fig. 3. Functional and physical manufacturing system components class diagram

Table 1. Manufacturing system components taxonomies

Class	Taxonomy	Taxonomy content
System layout	Operation paradigm	Job shop, DMS, cellular manufacturing, assembly line, FMS, FFMS or RMS [17].
	Shape	Product flow layout (the shape follow the material flow between stations): Line, U-Shaped, Loop or network [17], ladder shape (alternative paths for material flows) or Process layout (the division of shop-floor in cells follows the parts functions): Job shop or cellular shop.
	Segment flow [17]	Direction (Uni-directional or bi-directional), control (synchronous or asynchronous), flow control junction (one to one; one to many or many to many).
System control	Control structure	Direct, distributed or hierarchical [17]. .
Production unit	Production unit type	manufacturing cell, machine tool, work center for manufacturing; manual, hybrid or automated assembly single station assembly, single station assembly with set-wise assembly flow, single station assembly according to the once-piece-flow principle, multi-station assembly machine.
	Process technology	Primary shaping (casting from liquid, plastic, slurry, granular, fiber, gas or ionized shaped); Forming (pressure, compressive or tensile forming, bending or shearing forming); Separating (machining, cutting, lathe, drilling, milling, turning, refining); Joining (putting together, filling, pressing on/in, shapeless forming, welding, soldering, bonding or textile joining, brazing, soldering, sintering, fastening, system fixation (DIN 8593), Coating and Changing material property from different states (DIN 8580).
	Production facility	CNC, machine tools as Universal Machining Centres, Turning Centres, Drilling Machines, RMT, operators, robots. Their characteristics are their structure, tooling and fixtures [18].
	Identification facility	Camera, laser scanner, RFID sensors, bar code readers, smart card, embedded systems, wireless technology.
	Handling system	Robot with grippers, operator, artificial hands.
Storage system	Storage mode	FIFO; LIFO; Random access [17].
	Mean store time	Sorter buffer, short time store or buffer store, supply store or warehouse or long-time store or depot [16].
	Load carrier	Bins, trays, pallets, box pallets, movable storage racks, cassettes, container [16].
	Store place	Cross beams, powered rollers or buffer track.
	Storage device	High lift truck, fork lift truck, reach truck, narrow aisle stacker, storage and retrieval unit, transFaster, Shelf trolley, satellite shuttle and stacker crane [16].
	Load handling device	Fixed, movable or telescope fork, telescope table, push and pull device, roller table or chain conveyor [16].
Transportation	Transportation device	Conveyor, monorail, for lift truck, automated guided Vehicle [18], cranes, gantries, robots and feeder.
system	Transportation technology	Continuous (pipelines, belt conveyors) or non-continuous (conveyor system with powered track network, vehicle systems non powered track network) [16].
	Transportation system type (i.e. layout)	Its characteristics are: level (floor level or overhead [19]), working network (aisle, conveyor, overhead or column network [19]), connectivity characteristic (strength of connectivity, the capacity and directionality [19]), motion (uni or bi-directional, synchronous or asynchronous [18]), the path (fixed or variable [18]).

Acknowledgements

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